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DETECTION OF THE 67.9 KEV AND 78.4 KEV LINES ASSOCIATED WITH THE RADIO-ACTIVE DECAY OF ^{44}TI IN CASSIOPEIA A

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ABSTRACT

We report the detection of the ^{44}Sc nuclear decay lines at 67.9 keV and 78.4 keV associated with the nuclear decay of ^{44}Ti in Cassiopeia A. The line emission was observed by the PDS instrument on board BeppoSAX, which recently observed the supernova remnant for over 500 ks. The detection of the line emission with a flux of $(2.1 \pm 0.7)\ 10^{-5}$ ph/cm^2/s in each line (90% confidence) is at the 5σ significance level, if we can assume that the 12-300 keV continuum is adequately represented by a single power law. However, as the nature of the continuum is not clear we investigate various other possibilities. A more conservative estimate of the line flux is made by assuming that a power law continuum is at least a good approximation to the continuum emission for a narrower 30-100 keV energy range. With this limitation the measured line flux is $(1.9 \pm 0.9)\ 10^{-5}$ ph/cm^2/s, with the detection still at the 3.4σ significance level. We suggest that together with the CGRO-COMPTEL measurement of the ^{44}Ca line at 1157 keV of $(3.3 \pm 0.6)\ 10^{-5}$ ph/cm^2/s a flux for all three lines of $(2.5 \pm 1.0)\ 10^{-5}$ ph/cm^2/s for Cas A can be adopted. This implies an initial ^{44}Ti mass of $(0.8 - 2.5)\ 10^{-4}$ $M_\odot$.

Subject headings: gamma rays: observations – ISM: individual (Cassiopeia A) – nuclear reactions, nucleosynthesis, abundances – supernova remnants – X-rays: ISM

1. INTRODUCTION

The detection of gamma ray line emission at 1157 keV from the supernova remnant Cassiopeia A by CGRO-COMPTEL (Iyudin et al. 1994) led to renewed interest in the nucleosynthesis and properties of ^{44}Ti, the radio-active element with which this ^{44}Ca nuclear de-excitation emission is associated.

However, the decay chain $^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc} \rightarrow {}^{44}\mathrm{Ca}$ produces two other nuclear de-excitation lines of ^{44}Sc at 67.9 keV and 78.4 keV with a flux equal to that of the 1157 keV emission (see Diehl & Timmes (1998) for a review). As observations with the hard X-ray instruments CGRO-OSSE, RXTE-HEXTE and BeppoSAX-PDS failed to detect those lines (The et al. 1996; Rothschild et al. 1997; Vink et al. 2000), some doubt was cast on the observed 1157 keV line flux, if not on the detection itself. With subsequent observations by COMPTEL, the flux estimates changed from $(7.0 \pm 1.7)\ 10^{-5}$ ph/cm^2/s to $(3.3 \pm 0.6)\ 10^{-5}$ ph/cm^2/s (Iyudin 1997), whereas a 83 ks BeppoSAX-PDS spectrum narrowed the ^{44}Sc fluxes to a 99.7% upper limit of 4.1 10^{-5} ph/cm^2/s (Vink et al. 2000).

In this paper we report on a new, deep, exposure of Cas A with the BeppoSAX X-ray observatory. The BeppoSAX-PDS spectrum from this observation, together with archival data, finally gives a reliable estimate of the the 67.9 keV and 78.4 keV line fluxes.

2. OBSERVATIONS AND DATA

In May and June this year BeppoSAX observed Cas A for more than 500 ks. The primary goal of this observation was to detect the 67.9 keV and 78.4 keV nuclear decay lines with the hard X-ray Phoswich Detection System, PDS (Frontera et al. 1997). The PDS consists of four NaI(Tl)/CsI(Na) scintillation detectors behind two rocking collimators with a 1.3° field of view. During the observation the collimators switch back and forth between the on source position and two opposite off source positions, such that always one collimator observes the source and the other the background. Due to the alternating position of the collimators the effective exposure of the source with the PDS is about half the total observation time. In this case the effective PDS exposure is 256 ks. We used additional archival PDS spectra of on source Cas A observations, resulting in a total effective PDS exposure[5] of 311 ks.

As explained in the BeppoSAX analysis cookbook (Fiore et al. 1999), the standard software pipeline incorporates two methods for rejection of background events due to energetic particles. The more advanced method, which is preferred for a background dominated source like Cas A, uses a variable, energy-dependent, rise-time rejection threshold. This results in a better particle rejection, but at the cost of a 7% loss in effective area. Although this is the preferred method, to get a feel of the systematic errors involved, we also include some analysis of the same observations, but with spectra extracted using the constant rise-

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[5] The observational identification numbers for the additional archival data used for our analysis are 30011001, 30011002 and 30795005. They were chosen on the availability of spectra made with the variable rise time rejection method.

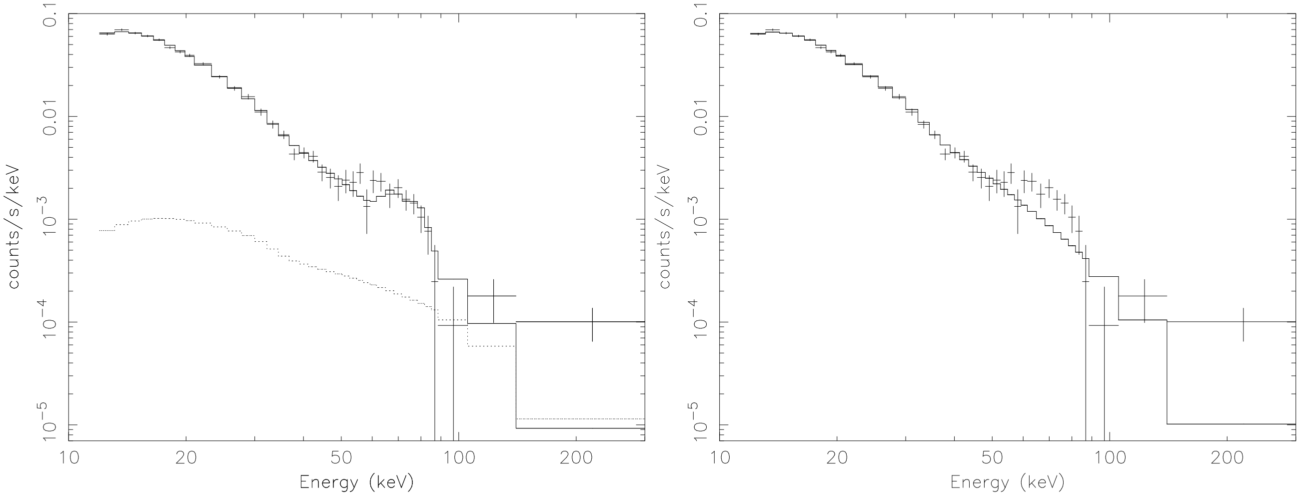

Fig. 1.— BeppoSAX-PDS spectrum of Cassiopeia A. The solid line in the left figure shows the spectral model including the ^{44}Sc lines at 68.9 keV and 78.4 keV. The dotted line shows the expected systematic error in the background subtraction, as estimated from blank field PDS spectra (Guainazzi & Matteuzzi 1997). The figure on the right shows the best fit power law model without ^{44}Sc lines. The channels above 80 keV have been rebinned for presentational purposes.

time rejection method. Compared with the statistical uncertainties, the measured ^{44}Sc flux does not depend much on the method chosen, but statistical errors are slightly larger for spectra that were extracted using the constant risetime method (Table 1).

There exists a well known error in the absolute flux density scale of the PDS instrument of a factor 0.86 ± 0.03. We took this factor and the 7% effective area loss into account by multiplying the response matrix by a factor 0.80. Although the statistical error of the flux calibration is small, there exists some scatter in this relation (Fiore et al. 1999). In view of this, and the small differences between measurements made using the two rise time rejection methods, we adopt a conservative 10% systematic error. In order to obtain reliable χ^2 statistics, the spectra were rebinned to channel widths of approximately $\Delta E/3$, where ΔE is the full width at half maximum (FHWM) energy resolution, which is about 9 keV at 75 keV. Further rebinning was not necessary as the data are background dominated, resulting in gaussian error distributions for each channel. We verified that the spectra of each collimator were consistent with the best fit model to the overall spectrum (see below). Similarly, we verified the consistency of the recently observed spectra and the archival spectra.

As far as we know there are no instrumental background lines coinciding in energy with the ^{44}Sc lines. Possible contamination sources of line emission close to the ^{44}Sc lines are tantalum from the collimator and the on board ^{241}Am calibration source. ^{241}Am emits photons at 60 keV, whereas the Ta Kα and Kβ transitions are at 57 keV and 65 keV with an emission ratio of 4:1. These lines may be responsible for a small emission excess around 60 keV (Fig. 1). However, adding these lines to our models changed the measured ^{44}Sc line flux with less than 5%; much smaller than the statistical uncertainty in the line flux.

Note that the observed power law normalization of the PDS spectrum agrees with that of the RXTE-HEXTE (Allen et al. 1997). At 15.9 keV their model fits imply $2.6\,10^{-4}$ ph/s/keV, whereas the PDS spectrum indicates $2.5\,10^{-4}$ ph/s/keV. The photon index above 16 keV of the RXTE-HEXTE spectrum, 3.04 ± 0.15, agrees within 1.6σ with the value reported below. The continuum normalization also agrees within 1.5σ with measurements by CGRO-OSSE (The et al. 1996), which measured a flux density of $(9.0 \pm 2.1)\ 10^{-7}$ ph/cm^2/keV at 100 keV, compared to $(5.8 \pm 0.8)\ 10^{-7}$ ph/cm^2/keV for our measurement, obtained from extrapolating the power law normalization to 100 keV (first row in Table 1). Note that the CGRO-OSSE had a much larger field of view ($11^\circ \times 4^\circ 4$) than the BeppoSAX-PDS.

3. DATA ANALYSIS

We present the combined PDS-spectrum and the simplest possible model, consisting of a power law continuum and two nuclear decay lines, in Figure 1. For this modeling of the continuum shape the ^{44}Sc lines are detected with a significance of more than 5σ ($\Delta\chi^2 = 30$). The flux in each line is $(2.1 \pm 0.7)\ 10^{-5}$ ph/cm^2/s and the photon index is 3.3 (see Table 1 for details). However, the nature of the hard X-ray continuum is still under debate. It has been argued that it is synchrotron radiation from shock accelerated electrons, or, alternatively, that it is bremsstrahlung emission caused by a non-thermal tail to the thermal electron distribution (Asvarov et al. 1990; Allen et al. 1997; Favata et al. 1997; Bleeker et al. 2001). A more specific bremsstrahlung model was worked out by Laming (2001a,b), who calculated the spectrum of electrons accelerated by lower hybrid waves associated with shocks in the ejecta.

In this letter we limit ourselves to the detection of the ^{44}Sc lines. We therefore leave a detailed discussion of the hard X-ray continuum, which should also include data for the energy range 0.5-10 keV, to a future article. However, in order to test the dependence of the measured line flux estimates on the assumed continuum shape we tested various continuum models, the results of which can be found in Table 1. It is surprising that the best fit to the PDS-spectrum in a statistical sense is provided by a power law model plus ^{44}Sc line emission. However, as the measured

line flux depends on the continuum model chosen, we have to take the uncertainty about the nature of the continuum into account.

It is clear from spectral fits to the narrower 30-100 keV spectral range that the inclusion of a thermal component with $kT_{\rm e}$= 4.2 keV has little effect on the estimated ^{44}Sc flux. Certainly, for this narrow range a power law is a reasonable approximation for the continuum. As the energy range is smaller, there is more statistical uncertainty about the photon index, and therefore the ^{44}Sc line flux is more uncertain. Indeed the significance of the line emission drops from the 5σ to the 3.4σ level. The photon index versus line flux confidence contours for this energy range is shown in Figure 2. The 3σ upper limit on the flux in both lines is 3.5 10^{-5} ph/cm^2/s, based on the 30-100 keV energy range. This upper limit is comparable to the ^{44}Ca line flux at 1157 keV recently obtained from CGRO-COMPTEL data, (3.3 ± 0.6) 10^{-5} ph/cm^2/s (68% confidence range), see Iyudin (1997). However, both measurements are consistent given the 25% systematic uncertainties for the COMPTEL measurement (Dupraz et al. 1997).

Although it is difficult to combine the COMPTEL and the PDS results, due to the unknown nature of the systematic errors, the fact that there are now two independent measurements of line emission associated with the ^{44}Ti decay increases the credibility of the detections. We therefore suggest adopting a ^{44}Sc/^{44}Ca line flux for Cas A of $(2.5 \pm 1.0)\,10^{-5}$ ph/cm^2/s, which is consistent with both the PDS and COMPTEL measurements.

4. CONCLUSIONS

Since the initial discovery of the ^{44}Ca nuclear decay lines by CGRO-COMPTEL (Iyudin et al. 1994), our knowledge of the formation and decay of ^{44}Ti has substantially improved. Recently, the decay time of ^{44}Ti has been accurately measured to be 85.4 ± 0.9 yr by three independent experiments (Ahmad et al. 1998; Görres et al. 1998; Norman et al. 1998). As the Cas A supernova was probably observed by the English astronomer J. Flamsteed in A.D. 1680 (Ashworth 1980), the age of Cas A is $\sim$ 320 yr. A good alternative is to use the kinematic age of the fast moving optical knots, 330 yr (Thorstensen et al. 2001), but the age difference is so small that it has little effect on the inferred range of initial ^{44}Ti mass. The line flux of $(2.5 \pm 1.0)\,10^{-5}$ ph/cm^2/s, combined with the ^{44}Ti decay time and a distance to Cas A of $3.4^{+0.3}_{-0.1}$ kpc (Reed et al. 1995), yields an initial ^{44}Ti mass in the range $(0.8 - 2.5)$ 10^{-4} M$_\odot$, with 1.2 10^{-4} M$_\odot$ corresponding to the adopted ^{44}Sc/^{44}Ca flux and distance to Cas A.

This is rather high compared to model predictions, which usually indicate ^{44}Ti masses below 10^{-4} M$_\odot$, except for progenitor masses around 12M$_\odot$ and above $\sim$25M$_\odot$ (Timmes et al. 1996). For that reason Mochizuki et al. (1999) made the interesting suggestion that the ^{44}Ti decay may be delayed, as a result of complete ionization of ^{44}Ti, inhibiting the decay of ^{44}Ti by the capture of a K-shell electron. However, recently Laming (2001c) showed that the electron temperature in the ejecta was probably never high enough to seriously affect the ^{44}Ti decay.

The production of ^{44}Ti increases with the size of the helium core of the progenitor, but material falling back on the neutron star or black hole limits the amount of ejected ^{44}Ti. Model calculations show that massive stars have more fall back, but pre-supernova wind loss may limit the amount of material falling back (Timmes et al. 1996). This agrees with the idea that the progenitor of Cas A was a not too massive ($\sim$ 30M$_\odot$) Wolf-Rayet star that suffered heavy mass loss (Vink et al. 1996). Additionally, assymetries in the explosion may have increased the amount of ^{44}Ti synthesized (Nagataki et al. 1998). The likely presence of a neutron star (Chakrabarty et al. 2001) in Cas A further constrains the explosion scenario for Cas A, as too much fall back would have resulted in the formation of a black hole.

Although we have now finally detected the ^{44}Sc nuclear decay lines at 67.9 keV and 78.4 keV, interesting observations remain to be done with future hard X-ray and Gamma-ray missions. The solid state detectors on board Integral will be able to measure the line broadening of the ^{44}Ca line accurately, and constrain the properties of the hard X-ray continuum further. In addition, hard X-ray experiments using multi-layer mirrors will be able to map the spatial distribution of ^{44}Ti in Cas A on the arcminute scale.

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REFERENCES

Ahmad, I., Bonino, G., Cini Castagnoli, G., Fischer, S. M., Kutschera, W., & Paul, M. 1998 PhRvL, 80, 2550
Allen, G. E., et al. 1997, ApJ, 487,L97
Arnaud, K. A. 1996, Astronomical Data Analysis Software and Systems V, eds. Jacoby G. & Barnes J., p17, ASP Conf. Series volume 101.
Ashworth, W. B. 1980, J. Hist. Ast., 11, 1
Asvarov, A. I., Dogiel, V. A., Guseinov, O. H., & Kasumov, F. K. 1990, A&A, 229, 196
Bleeker, J., Willingale, R., van der Heyden, K., Dennerl, K., Kaastra, J., Aschenbach, B., & Vink, J. 2001, A&A, 365, L225
Chakrabarty, D., Pivovaroff, M. J., Hernquist, L. E., Heyl, J. S., & Narayan, R. 2001, ApJ, 548, 800
Chevalier, R.A., & Kirshner, R.P. 1979, ApJ, 233, 154
Diehl, R., & Timmes, F. X. 1998, PASP, 110, 637
Dupraz, C., et al. 1997, A&A, 324, 683
Favata, F., et al. 1997, A&A, 324, L49
Fiore F., Guainazzi M., & Grandi P. 1999, "Handbook for BeppoSAX NFI Spectral Analysis", BeppoSAX Science Data Center, Rome
Frontera, F., et al. 1997, A&AS, 122, 357
Guainazzi, M., & Matteuzzi, A. 1997, BeppoSAX Science Data Center, technical report - TR-011
Görres, J., et al. 1998, PhRvL, 80, 2554
Green D.A. 2000, 'A Catalogue of Galactic Supernova Remnants (2000 August version)', MRAO, Cavendish Laboratory, Cambridge, UK (available at "http://www.mrao.cam.ac.uk/surveys/snrs/").
Iyudin A. F., et al. 1994, A&A, 284, L1
Iyudin A. F. 1997, Nuclear Phys. A, 654, 900c
Laming, J. M. 2001a, ApJ, 546, 1149

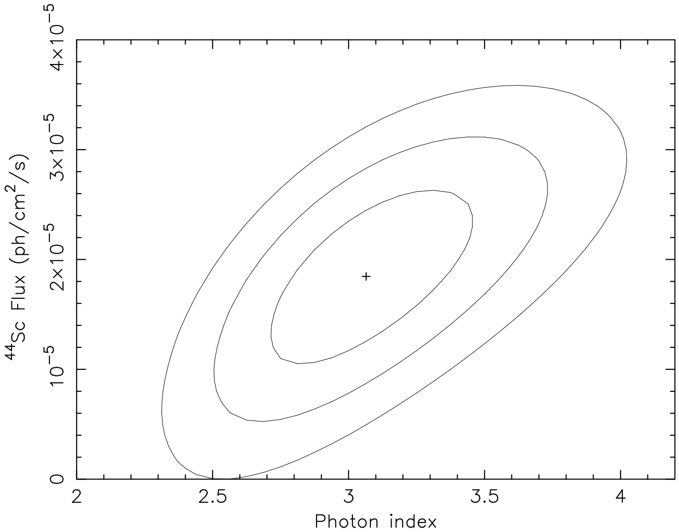

Fig. 2.— Confidence ellipses for the combination of power law index and ^{44}Sc flux for the spectral energy range of 30 keV to 100 keV. The contours are 1, 2 and 3σ 2-parameter confidence levels ($\Delta\chi^2 = 2.3, 6.17, 11.8$, see Lampton et al. (1976)).

Laming, J. M. 2001b, ApJ, 563, in press (astro-ph/0108285)
Laming, J. M. 2001c, Proc. of Joint SOHO-ACE Workshop 2001, Solar and Galactic Composition, ed. R.F. Wimmer-Schweingruber, in press (astro-ph/0108316)
Lampton, M., Margon, B., & Bowyer, S. 1976, ApJ, 208, 177
Mewe, R., Kaastra, J. S., & Liedahl, D. A. 1995, Legacy 6, 16
Mochizuki, Y., Takahashi, K., Janka, H. T., Hillebrandt, W., & Diehl, R. 1999, A&A, 346, 831
Nagataki S., Hashimoto, M., Sato, K., Yamada, S., Mochizuki, Y.S. 1998, ApJ, 492, L45
Norman, E.B., et al. 1998, PhRvC, 57, 2010
Reed, J. E., Hester, J. J., Fabian, A. C., Winkler, P. F. 1995, ApJ, 440, 706
Reynolds, S. P., & Keohane, J. W. 1999, ApJ, 525, 368
Rothschild, R. E., et al. 1997, Nuclear Phys. B (Proc. Suppl.), 69/1-3, 68
The, L.-S., et al. 1996, A&AS, 120, 357
Thorstensen, J.R., Fesen, R. A., & van den Bergh, S. 2001, AJ, 122, 297
Timmes, F. X., Woosley, S. E., Hartmann, D. H., & Hoffman, R. D. 1996, ApJ, 464, 332
Vink, J., Kaastra, J., Bleeker, J. 1996, A&A, 307, L41
Vink, J., Kaastra, J., Bleeker, J., & Bloemen, H. 2000, AdSpR, 25, 689

Table 1

Summary of spectral model fits.

RT method	model	spectral range (keV)	^{44}Sc flux (10^{-5} ph/cm^2/s)	PL index	PL norm @ 1 keV (ph/s/keV)	radio index	roll off energy (keV)	Emission measure[a] (10^{12} cm^{-5})	χ^2/ν
V	PL	12 - 300	2.1 ± 0.7	3.30 ± 0.05	2.3 ± 0.3				69.5/63
V	PL+therm.	12 - 300	1.0 ± 0.7	2.71 ± 0.06	0.28 ± 0.05			9.25[b](fixed)	96.7/63
V	PL+therm.	12 - 300	2.0 ± 0.7	3.2 ± 0.2	1.8 ± 0.8			$1.3 (< 4.5)$	69.4/62
V	*sresc*+therm.	12 - 300	3.2 ± 0.8			$0.85\ (> 0.848)$[c]	9.2 ± 0.3	9.25[b](fixed)	120.8/63
V	*sresc*+therm.	12 - 300	2.8 ± 0.9			$0.85\ (> 0.838)$[c]	10 ± 1	5.8 ± 0.9	75.9/62
V	PL	30 - 100	1.9 ± 0.9	3.1 ± 0.4	$0.9^{+3.6}_{-0.7}$				15.6/20
V	PL+therm.	30 - 100	1.8 ± 0.9	3.0 ± 0.04	$0.7^{+2.8}_{-0.6}$			9.25 (fixed)	15.5/20
C	PL	12 - 300	2.5 ± 0.8	3.33 ± 0.06	2.5 ± 0.4				74.5/63
C	PL	30 - 100	1.7 ± 1.0	2.8 ± 0.5	$0.30^{+1.51}_{-0.24}$				18.7/20

Note. — All spectral models can be found in X-ray spectral analysis package *xspec* v11 (Arnaud 1996). The first column indicates which background rejection criterium was used, - variable (V), or constant (C) - to obtain the source spectrum (see text). The ^{44}Sc lines were modelled by two deltalines with energies fixed at 67.9 keV and 78.4 keV, and equal line flux. PL is short for power law. We used *vmekal* (a collisional equilibrium model) for the thermal component (Mewe et al. 1995). The *sresc* model is described in Reynolds & Keohane (1999); it gives the synchrotron emission from a relativistic power law distribution of particles with an exponential cut-off. Errors are statistical errors, and correspond to 90% confidence intervals.

[a]The emission measure is defined as $\frac{n_{\rm H} n_{\rm e} V}{4\pi d^2}$. Note that in order to keep in line with models used by Vink et al. (1996), Favata et al. (1997) and Vink et al. (2000) we used a plasma enhanced in helium and nitrogen by a factor 10 (based on optical observations of the shocked circumstellar medium, e.g. Chevalier & Kirshner (1979)). The electron temperature was fixed to $kT_{\rm e}$= 4.2 keV (Vink et al. 2000). Note that the ejecta is most likely the main source of thermal X-ray emission in Cas A, and so an O-rich composition could also be a reasonable model. This would not, however, make any difference to the shape of the thermal continuum at photon energies relevant here.

[b]The fixed emission measure is identical to that used by Vink et al. (2000), comparing with ASCA-SIS0 and BeppoSAX-MECS data shows that this implies that below 10 keV about half of the continuum is thermal, whereas the other half comes from an additional component.

[c] We allowed the radio spectral index, nominally 0.77 for Cas A, to vary in the range 0.7 to 0.85; the normalization parameter is the radio flux density at 1 GHz, which was fixed to 2720 Jy (Green 2000). The parameters derived from this model should be treated with caution, as the values for radio index and roll off energy are highly correlated.